Decadal Variations of Snow Cover

DAVID A. ROBINSON[1]

ABSTRACT

In situ and satellite observations of snow-cover duration show a considerable amount of year-to-year variability on local to hemispheric scales. This variability is often embedded in longer-term fluctuations. In situ data from the central United States indicate multi-decadal fluctuations in the duration of snow over the past century, and hemispheric satellite observations suggest variations lasting for several years or more.

Such analyses have become possible in recent years as a result of the recovery, digitization, and validation of historic in situ observations of snow cover and the availability of two decades of satellite observations of continental snow cover. Efforts are needed to recover additional historic data, to improve the recognition of snow using microwave satellite data, and to create global snow products using all available data sources. With these data available for analysis, knowledge of the spatial and temporal kinematics of snow cover will continue to improve. This will contribute to a better understanding of the role of snow in the climate system and to the utility of snow as an indicator of climate change.

INTRODUCTION

Snow cover is a critical influence on the earth's climatic energy and hydrologic budgets. In many regions it may play an influential role in determining the magnitude of any human-induced climate change, and might be a useful indicator and monitor of such change. To understand better the importance of snow in the climate system, it is essential that accurate information on the temporal and spatial dimensions of snow cover be available. Such data have been obtained through in situ and satellite observations, and recent efforts have begun to locate, assimilate, and validate these data. Once available, they are being employed in empirical and modeling investigations of snow-cover kinematics and the dynamical aspects of snow within the climate system. An excellent survey of the latter is provided by Walsh (1995) earlier in this section. This paper will concentrate on the distribution of snow cover in space and time over the past two decades and the past century. Much of the discussion will focus on the newly available in situ and satellite data sets. Given the lack of attention paid to secular snow cover data until recently, only limited analyses of these data have taken place. A few examples of these efforts

[1]Department of Geography, Rutgers University, New Brunswick, New Jersey

will be presented. For information on snowfall and its long-term variability across the North American continent, the paper later in this section by Groisman and Easterling (1995) is recommended.

IN SITU OBSERVATIONS

In situ snow-cover data are gathered mainly over land. Only a few short-term studies have measured snow on sea ice or ice sheets (e.g., Hanson, 1980). Most observations on land are made on a once-per-day basis. The general practice is to record the average depth of snow lying on level, open ground that has a natural surface cover. At primary stations, the water equivalent of the snowpack may also be measured. In some regions, snow courses have been established where snow depth, water equivalent, and perhaps other pack properties are measured along prescribed transects across the landscape. Observations are often made only once per month, and the number of courses is extremely limited in North America. More frequent and abundant course data are gathered in the Commonwealth of Independent States, and currently this information is being recovered through a cooperative effort between the U.S. National Snow and Ice Data Center (NSIDC) at the University of Colorado and A. Krenke of the Russian Academy of Sciences.

Current station observations of snow cover are of a sufficient density for climatological study in the lower elevations of the middle latitudes. Elsewhere, while data of a high quality are gathered at a number of locations (Barry, 1983), the spatial and temporal coverage of the information is often inadequate for climate study. There is no hemispheric snow-cover product based entirely on station reports. The U.S. Air Force global snow-depth product depends heavily on surface-based observations as input into a numerical model that creates daily charts with global coverage, but it must rely on extrapolations and climatology in data-sparse regions (Hall, 1986; Armstrong and Hardman, 1991). There have been a number of regional snow-cover products over the years that are based on station data. Of greatest longevity are the Weekly Weather and Crop Bulletin charts, which have been produced since 1935. These, and the daily NOAA charts, are produced for the conterminous United States mainly from first-order station observations. Therefore, neither has a particularly high resolution, and observations may be influenced by urban heat-island effects.

In a number of countries, there are numerous stations with relatively complete records of snow extending back 50 years or more (Barry and Armstrong, 1987). Until recently, most data have remained unverified and disorganized (Robinson, 1989). As a result, few studies have dealt with long-term trends or low-frequency fluctuations of snow over even small regions (e.g., Arakawa, 1957; Manley, 1969; Jackson, 1978; Pfister, 1985). Through the cooperative efforts of a number of scientists and data centers, this situation has begun to be rectified. Examples include the exchange of data through the US/USSR Bi-Lateral Environmental Data Exchange Agreement and between the Lanzhou Institute of Glaciology and Geocryology and both Rutgers University and the NSIDC. These and other data are in the process of being quality controlled, and routines to fill in gaps in snow-cover records are being developed (Hughes and Robinson, 1993; Robinson, 1993a). Clearly, there is a need to continue efforts to identify, assimilate, in some cases digitize, and in all cases validate station and snow-course observations from around the world. These data must also must be accompanied by accurate and complete metadata.

Lengthy in situ records continue to be analyzed for individual stations, and data from networks of stations have begun to be studied on a regional level. For example, marked year-to-year variability in snow-cover duration is recognized over the course of this century at Denison, Iowa (Figure 1). Snow at least 7.5 cm deep has covered the area for as much as 80 percent of the winter, but in a number of years no or only a few days have had a cover this deep. Overall, the duration of winter and spring cover was at a maximum in the 1970s, and fall cover peaked in the 1950s. Other periods of more frequent winter cover include the 1910s and the late 1930s to early 1940s. The 1920s, middle 1940s, and late 1950s to early 1960s were periods with less abundant winter cover. Missing data around 1950 prohibit a direct assessment of winter cover at Denison, but adjacent stations suggest cover was scarce at this time. All three seasons show a greater abundance of snow-cover days in the past 40 years than in the first half of the century.

Efforts are under way to develop gridded snow files for a large portion of the central United States, using data from several hundred stations. Raw and filtered winter records from four of these stations are shown in Figure 2. They are for days with snow cover $\geq$7.5 cm, and all indicate long-term fluctuations on the order of one to several decades. The Nebraska and Kansas stations show maximum durations during the past several decades, with a similar early maximum at Oshkosh, Nebraska, in the 1910s and early 1940s. Late 1920s, early 1950s, and 1970s maxima were observed at Dupree, South Dakota, the latter two ending abruptly shortly thereafter. The North Dakota station had maximum winter snow cover in the 1930s, around 1950, and in the late 1970s. The range in filtered values over the period of record was approximately two weeks in Kansas and Nebraska and seven weeks in South Dakota and North Dakota.

SATELLITE OBSERVATIONS

Snow extent is monitored using data recorded in short-wave (visible and near-infrared) and microwave wave-

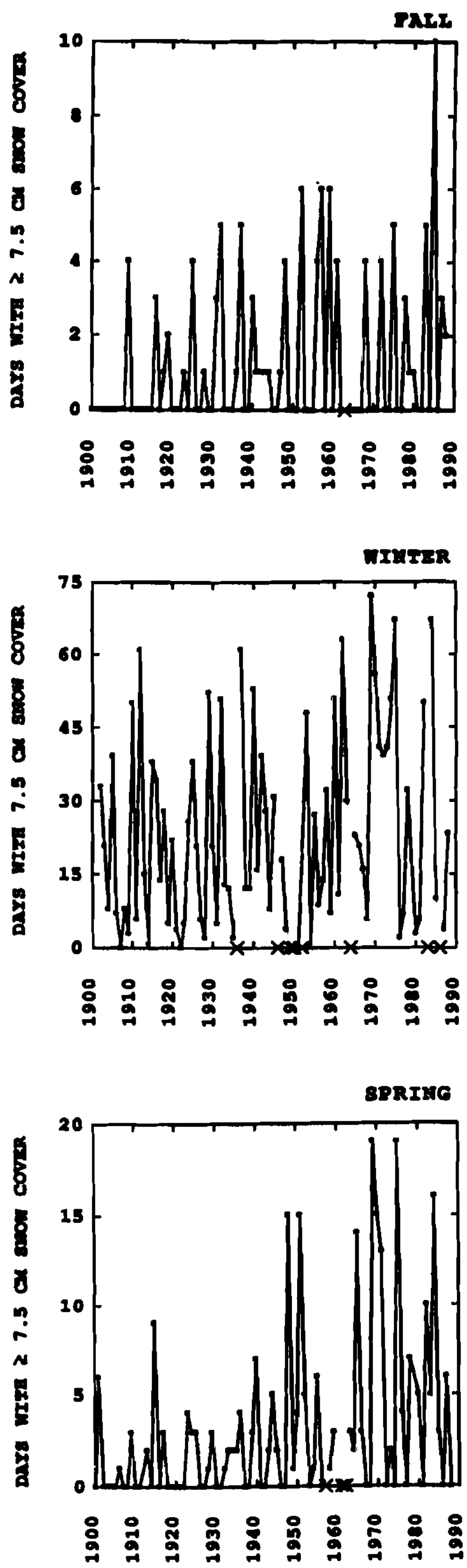

FIGURE 1 Time series of fall (September-November), winter (December-February), and spring (March-May) days with ≥7.5 cm of snow cover at Denison, Iowa. Missing years are marked with an X.

lengths by sensors on board geostationary and polar orbiting satellites. Retrieval techniques, the strengths and limitations of each spectral region for sensing snow, and the snow products derived using short-wave and microwave input are discussed in this section. The secular remote sensing of snow over Northern Hemisphere lands will be the principal focus; only a few efforts have addressed this over Southern Hemisphere lands (Dewey and Heim, 1983) or Arctic sea ice (Robinson et al., 1992).

Short-Wave and Microwave Snow Charting

Short-wave data provide continental coverage of snow extent at a relatively high spatial resolution. Snow is identified by recognizing characteristic textured surface features and brightness. Information on surface albedo and percentage of snow coverage (patchiness) is also gleaned from the data. Shortcomings include (1) the inability to detect snow cover when solar illumination is low or when skies are cloudy, (2) the underestimation of cover where dense forests mask the underlying snow, (3) difficulties in distinguishing snow from clouds in mountainous regions and in uniform, lightly vegetated areas that have a high surface brightness when covered with snow, and (4) the lack of all but the most general information on snow depth (Kukla and Robinson, 1979; Dewey and Heim, 1982).

Microwave radiation emitted by the earth's surface penetrates winter clouds, permitting an unobstructed signal from the surface to reach a satellite. The detection of snow cover from microwave data is possible mainly because of differences in emissivity between snow-covered and snow-free surfaces. Estimates of the spatial extent, as well as of the depth or water equivalent, of the snowpack are derived from equations that employ measurements of radiation sensed by multiple channels in the microwave portion of the spectrum (e.g., Kunzi et al., 1982; McFarland et al., 1987). Estimates of snow cover have been made using microwave data since the launch of the Scanning Multichannel Microwave Radiometer (SMMR) in late 1978. The spatial resolution of the data is approximately several tens of kilometers. Since 1987, close to the time of SMMR failure, the Special Sensor Microwave Imager (SSM/I) has provided data. Both sensors, having nearly the same spectral characteristics, have similar levels of success in monitoring snow extent (cf. the SMMR analyses below).

As with short-wave products, the microwave charting of snow extent is not without its limitations. The resolution of the data makes the detailed recognition of snow cover difficult, particularly where snow is patchy, and it is difficult to identify shallow or wet snow using microwaves. Also, the lack of sufficient ground-truth data on snow volume, wetness, and grain size makes an adequate assessment of the reliability of microwave estimates uncertain. The influence of a forest canopy on microwave emissions in snow-

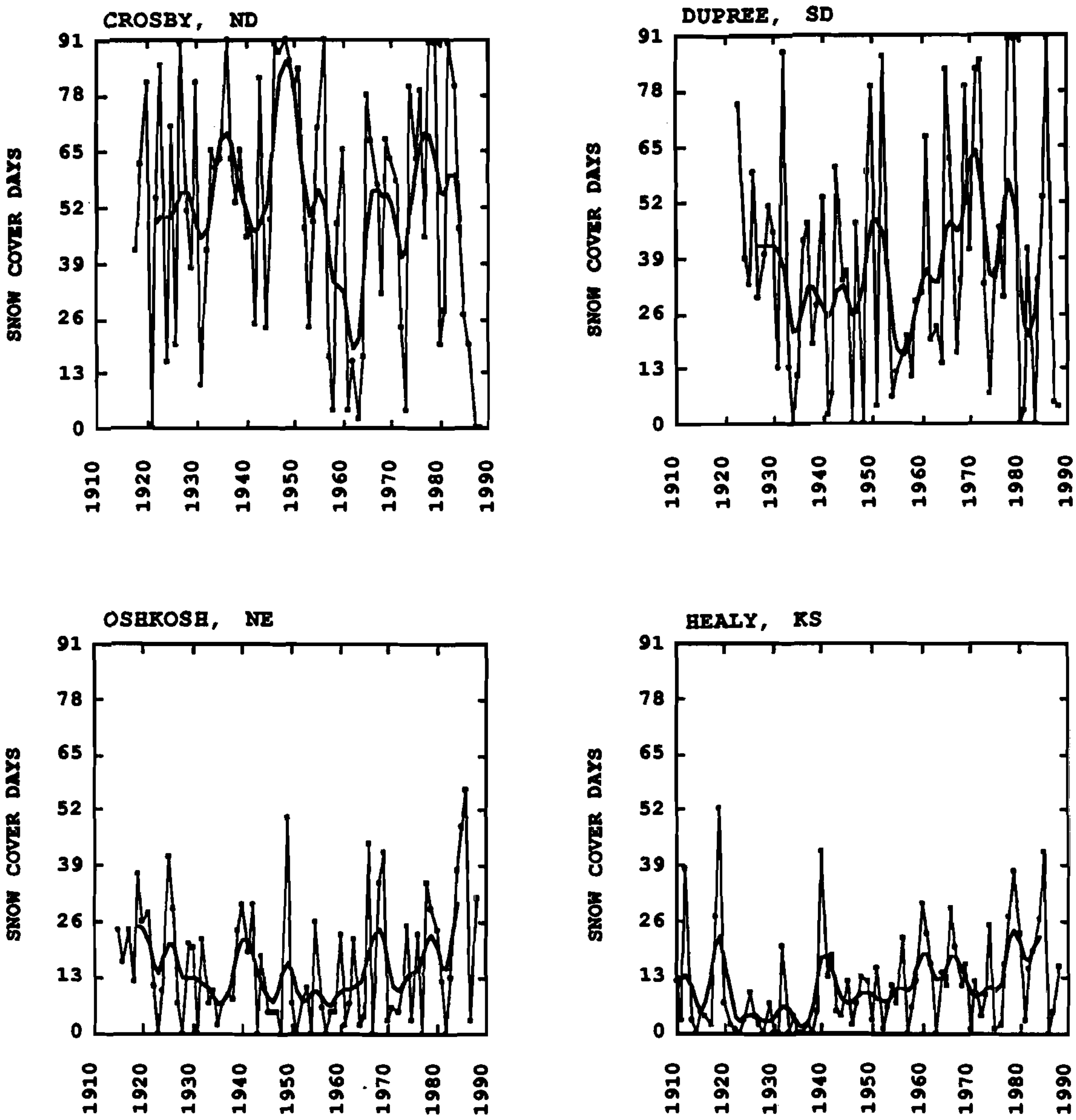

FIGURE 2 Time series of winter days with ≥7.5 cm of snow cover at four stations on the U.S. Great Plains. Also shown smoothed with a nine-point binomial filter, with only those points plotted where nine years are available for filtering (i.e., plotted year ±4 yr).

covered regions, which is currently not well understood, must also be taken into account when estimating snow cover. Because of the region-specific differences in land cover and snowpack properties, no single algorithm can adequately estimate snow cover across Northern Hemisphere lands.

Hemispheric Snow Products: NOAA Weekly Charts

In 1966, NOAA began to map snow cover over Northern Hemisphere lands on a weekly basis (Matson et al., 1986). That effort continues today, and remains the only such hemispheric product. NOAA charts are based on a visual interpretation of photographic copies of short-wave imagery by trained meteorologists. Up to 1972, the sub-point resolution of the meteorological satellites commonly used was around 4 km; since then it has become, and remained, close to 1.0 km. Charts show boundaries on the last day that the surface in a given region was seen. Since May 1982, dates when a region was last observed have been placed on the charts. An examination of these dates shows the charts to be most representative of the fifth day of the week.

It is recognized that in early years the snow extent was underestimated on the NOAA charts, especially during fall. Charting improved considerably in 1972 with the improvement of sensor resolution, and since then charting accuracy has been such that this product is considered suitable for continental-scale climate studies (Kukla and Robinson, 1981). The NOAA charts are most reliable where skies are frequently clear, solar illumination is high, snow cover is reasonably stable or changes slowly, and pronounced local and regional signatures are present owing to the distribution of vegetation, lakes, and rivers.

The NOAA charts are digitized on a weekly basis using the National Meteorological Center Limited-Area Fine Mesh grid. This is an 89 × 89 cell Northern Hemisphere grid, with cell resolution ranging from 16,000 to 42,000 km^2. If a cell is interpreted as being at least 50 percent snow covered, it is considered to be completely covered; otherwise it is considered to be snow free. Inconsistencies in the designation of a cell as land or water have occurred in the past during the digitization process. This has recently been resolved for the approximately 100 cells in question through the use of digital map files analyzed on a geographic information system (Robinson, 1993b).

A new routine for calculating monthly snow areas from the NOAA data has also recently been developed (Robinson, 1993b). This has eliminated previous inconsistencies resulting from undocumented changes in the methods used by NOAA to calculate the monthly values (Robinson et al., 1991). The new Rutgers Routine calculates weekly areas from the digitized snow files and weights them according to the number of days of a given week that fall in the given month. A chart week is considered to center on the fifth day of the published chart week (cf. above). No weighting has been employed in the NOAA routines.

Hemispheric Snow Products: NASA Microwave Files

Monthly charts of Northern Hemisphere continental snow extent have been produced from SMMR data by NASA scientists (Chang et al., 1990). The only such time series available to date, it covers the interval from November 1978 through August 1987. A single algorithm is used to estimate snow depth on a 0.5° × 0.5° grid. This theoretical algorithm uses the difference in brightness temperatures of 18 and 37 GHz SMMR data to derive a snow-depth/brightness temperature relationship for a uniform snow field. A snow density of 0.3 g/cm^3 and a snow-crystal radius of 0.3 mm are assumed; fitting the differences to the linear portion of the 18 and 37 GHz responses permits the derivation of a constant that is applied to the measured differences. This algorithm can be used for snow up to 1 m deep.

The monthly depth estimate for a given grid cell is calculated by averaging depths reported for the five or six pentad charts centered in a given month (SMMR data are gathered every other day and three of these passes are used for each pentad chart; there is a one-day gap between each pentad). If the average is $\geq$2.5 cm, the cell is considered to be covered with snow for the whole month. This methodology biases the snow areas to the high side, especially in those areas and periods where snow cover fluctuates.

Northern Hemisphere Continental Snow Cover: 1972-1992

According to the NOAA snow charts, the extent of snow cover over Northern Hemisphere lands varies from 46.5 million km^2 in January to 3.9 million km^2 in August (Table 1); most of August's snow lies on top of the Greenland ice sheet. The past two decades of monthly data are close to normally distributed, and monthly standard deviations range from 0.9 million km^2 in August to 2.9 million km^2 in October. The annual mean cover is 25.5 million km^2 with a standard deviation of 1.1 million km^2. The snowiest year was 1978, which had a mean of 27.4 million km^2; 1990 was the least snowy at 23.2 million km^2. Eight of the monthly minima for the two decades occurred in 1990.

With only two decades of reliable hemispheric information, it is impossible to identify anything in the way of trends or cycles in the temporal or spatial distribution of snow. What has become recognizable during the period of record is a tendency for multi-year departures in snow cover, in which less pronounced month-to-month and season-to-season departures are embedded. Twelve-month running means illustrate the periods of above-normal cover that occurred in the late 1970s and mid-1980s, and the lower and below-normal extents during the mid-1970s and early 1980s (Figure 3). The most significant lengthy departure during the past 20 years began in the late 1980s and continued into 1992. Of the 65 months between August 1987 and December 1992, only eight had above-normal snow cover. Three of these eight were September, November, and December 1992.

Spring cover has shown pronounced deficits over the past five years in Eurasia and six years in North America; areas in these springs have been at or below lows established before this period (Figure 4). During the same interval, both continents have had low seasonal cover in the fall and summer, although frequently neither continent has been at or approached record low levels. Winter cover has been close to average over the past six years.

The NOAA snow estimates are considered the most accurate figures available. Despite the positive methodologically induced bias of the monthly NASA estimates (cf. the previous section), they range from less than 1 million up to 13 million km^2 below the NOAA area estimates for those nine years for which both agencies provide estimates. These absolute differences are greatest in the late fall and early winter. In a relative sense, microwave areas are between 80 and 90 percent of short-wave values in winter and spring, 20 to 40 percent of the short-wave estimates in summer, and 40 to 70 percent of short-wave areas in fall. Possible explanations for the significant disparities in the latter two seasons are wet and shallow snows. These are difficult if

TABLE 1 Monthly and Annual Snow Cover (million km^2) over Northern Hemisphere Lands, Including Greenland

	Maximum (yr)	Minimum (yr)	Mean*	Median	Standard Deviation
Jan	49.8 (1985)	41.7 (1981)	46.5	46.1	1.8
Feb	51.0 (1978)	43.2 (1990,92)	46.0	45.6	2.0
Mar	44.1 (1985)	37.0 (1990)	41.0	40.8	1.9
Apr	35.3 (1979)	28.2 (1990)	31.3	31.4	1.8
May	24.1 (1974)	17.4 (1990)	20.8	20.6	1.9
Jun	15.6 (1978)	7.3 (1990)	11.6	11.4	2.1
Jul	8.0 (1978)	3.4 (1990)	5.3	5.5	1.2
Aug	5.7 (1978)	2.6 (1988,89,90)	3.9	3.8	0.9
Sep	7.9 (1972)	3.9 (1990)	5.6	5.6	1.1
Oct	26.1 (1976)	13.0 (1988)	17.6	17.5	2.9
Nov	37.9 (1985)	28.3 (1979)	33.0	32.8	2.3
Dec	46.0 (1985)	37.5 (1980)	42.5	42.7	2.3
Annual	27.4 (1978)	23.2 (1990)	25.5	25.4	1.1

*Means are for the period January 1972 through May 1992; extremes are for January 1972 through December 1992.

not impossible to monitor using microwaves. Depth may be the more important of these two variables, given the better agreement in spring, although it has been suggested that unfrozen soil beneath the pack is a major contributor to the underestimates during fall (B. Goodison, pers. commun.). The 85-GHz channel on the SSM/I has shown promise in improving the monitoring of shallow (<5 cm) snow cover (Nagler and Rott, 1991).

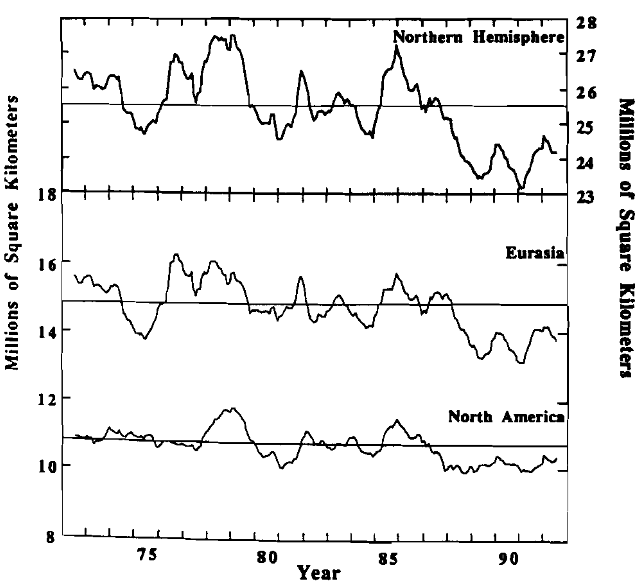

FIGURE 3 Twelve-month running means of snow cover over Northern Hemisphere lands (including Greenland) for the period January 1972 through December 1992. Running means are also shown for Eurasia and North America (including Greenland). Values are plotted on the seventh month of the twelve-month interval.

CONCLUSIONS

Significant strides have been made in recent years in the recovery, digitization, and validation of in situ observations of snow cover and their assimilation into regional networks. The availability of this information, in some cases going back to the turn of the century, complements the more recent global monitoring of snow from satellites. Analyses of both in situ and satellite observations show a considerable amount of year-to-year variability in the duration of snow cover on local to hemispheric scales. However, it is beginning to be recognized that this variability is often embedded in longer-term fluctuations. In situ data from the central United States points to multi-decadal fluctuations in the duration of snow over the past century, and the hemispheric satellite observations suggest variations lasting on the order of several years.

Efforts must continue to ensure the recovery and digitization of all available historic in situ observations, from both stations and snow courses. On the satellite side, the NOAA weekly product must continue to be produced in its present form. To abruptly or, perhaps more seriously, subtly alter the manner in which these charts are produced would severely weaken what is at present the longest and most consistent satellite-derived data set for any surface or atmospheric variable. Coincident with this must be efforts to improve the hemispheric monitoring of snow from microwave data using composited regional algorithms. Ultimately the goal must be to integrate all surface and satellite sources in a series of products reporting snow extent, depth and water equivalent, and regional surface albedo. These data should cover not only Northern Hemisphere lands but also lands in the Southern Hemisphere, ice sheets, and sea ice. Means

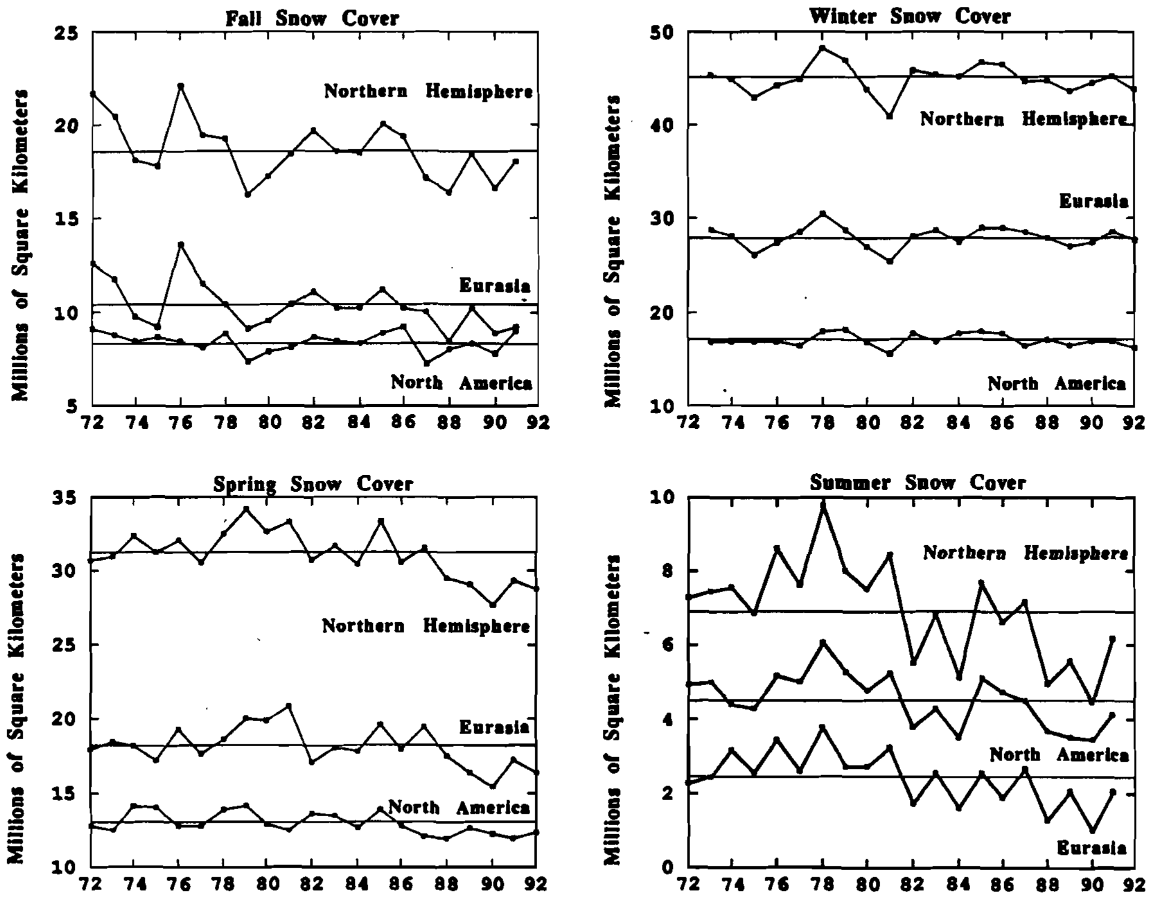

FIGURE 4 Seasonal time series of snow cover over Eurasia and North America (Greenland is excluded).

of integrating satellite and integrative products with earlier in situ observations must also be improved to provide the longest, most consistent records possible.

With adequate data available to analyze, knowledge of the spatial and temporal kinematics of snow cover over recent decades or even the past century will continue to improve. This will contribute to a better understanding of the role of snow in the climate system and to the utility of snow as an indicator of climate change.

ACKNOWLEDGMENTS

Thanks to G. Stevens at NOAA for supplying digital snow data and to A. Chang at NASA for providing microwave data. Thanks also to A. Frei, M. Hughes, and J. Wright at Rutgers for technical assistance. This work is supported by NOAA under grant NA90AA-D-AC518, and by the Geography and Regional Science Program of the National Science Foundation under Grant SES-9011869.